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Observed and Predicted Liquefaction of a Sand Stratum

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SYNOPSIS. Field observations and preliminary studies had led to the conclusion that the sand stratum liquefied only in a limited area during the March 14, 1979 earthquake. Further field studies revealed the presence of the sand layer throughout the Enmedio Island. This fact raised questions as to whether the sand liquefied or not in the whole area.

To clarify this question, a research program which included cyclic triaxial testing and numerical analyses was undertaken. The results of this study show that the sand layer did liquefy through the Island; however, due to differences in stratigraphic characteristics, superficial signs of liquefaction were developed only in a restricted zone.

INTRODUCTION

On March 14, 1980 a 7.6 magnitude earthquake shook the Enmedio Island inducing liquefaction in some parts of the Island (zone 2) as shown in fig 1. The fact that the phenomenon was not observed in zone 1 was rather puzzling, since the layer of fine sand which liquefied was found throughout the Island.

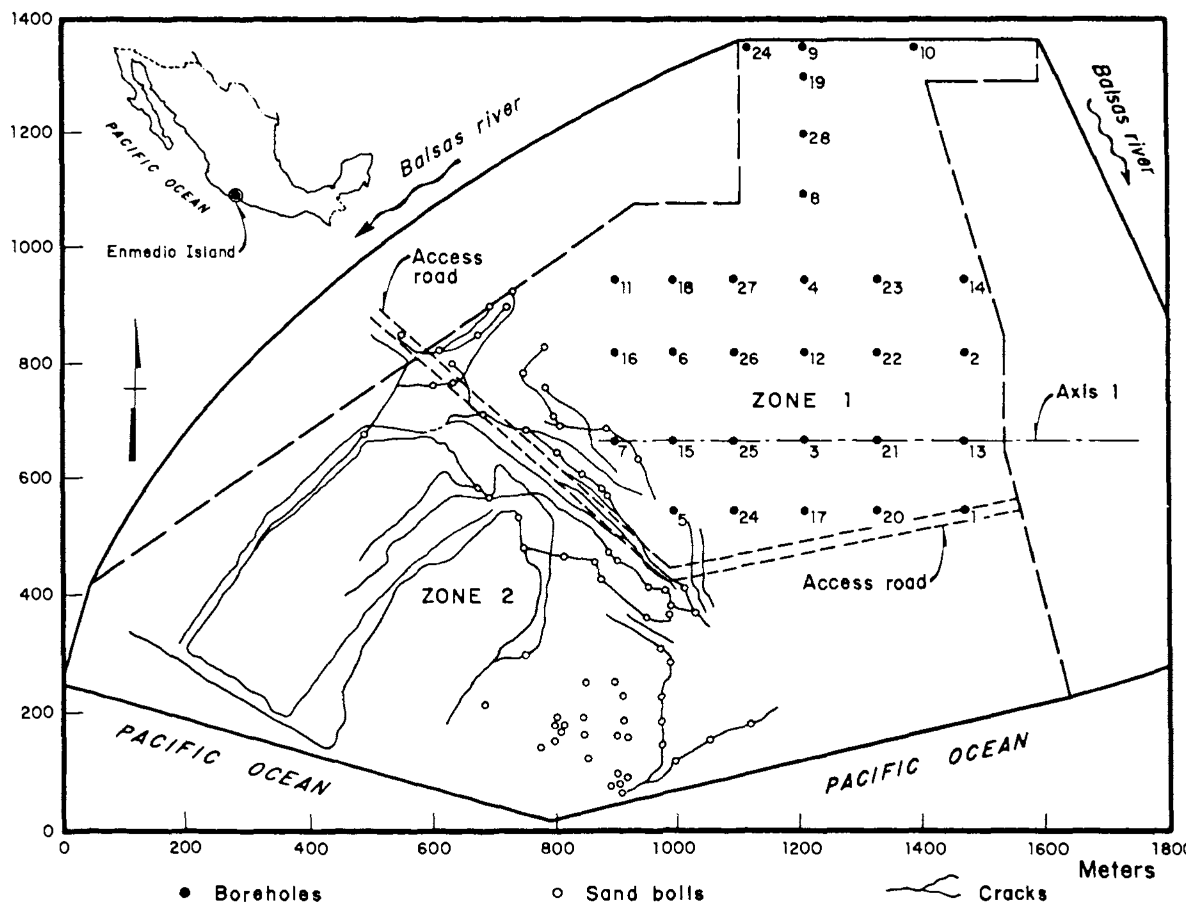


Fig 1. Plan view of the site. Boring location and observed damage cracks and sand boils

Since the different behavior of zones 1 and 2 could not be rationally explained on the basis of the available information and because of the importance of some of the structures to be built in zone 1, a second field exploration program was carried out. The results of this study revealed the existance of a discontinuos impervious layer of clay overlying the stratum of fine sand which liquefied. Also, it was realized that a different overburden pressure existed on both zones.

In order to define to what extent the presence of the pervious upper boundary and the greater confining pressure influenced the behavior of the sand deposit of zone 1, a research program including cyclic triaxial tests on reconstituted sand samples and numerical analyses was carried out. The results of this study are presented in this paper.

OBSERVED FIELD BEHAVIOR

The earthquake shaking produced two cracking systems. One along the access road and other parallel to the road, as shown in fig 1. The width of the cracks varied from 5 to 10 cm, indicating the order of magnitude of the horizontal ground displacements.

Sand boils were also developed during the seismic event, and according to an eyewitness they appeared just before the end of the shaking. This means that the pressure build-up was gradual and if it is considered that the strong part of the earthquake lasted about 15 seconds, it may be concluded that it took about 9 to 13 seconds for the liquefaction phenomenon to develop. A ground subsidence of few centimeters was also observed in zone 2.

"Geysers" of a sand-water mixture about 2 m high were observed towards the end of the earthquake. This shows that the earthquake-induced pore water pressure reached a value greater than the overburden pressure for a few seconds.

All these manifestations of liquefaction were observed only at the South and Southwest of the Island (fig 1) in spite of the fact that the layer of sand which liquefied was found throughout the Island (fig 2). It seems that the small differences in stratigraphic characteristics and in confining stresses between zones 1 and 2 prevented liquefaction or at least avoided its superficial manifestation in zone 1.

TEST PROGRAM

The material used in the cyclic triaxial tests was the fine sand composing the layer which liquefied. The main characteristics of the sand are given in Table I, and the envelopes of the grain distribution curves obtained from several sand samples are shown in fig 3. Also, in this figure, the grain distribution selected for the tests is indicated with a solid line.

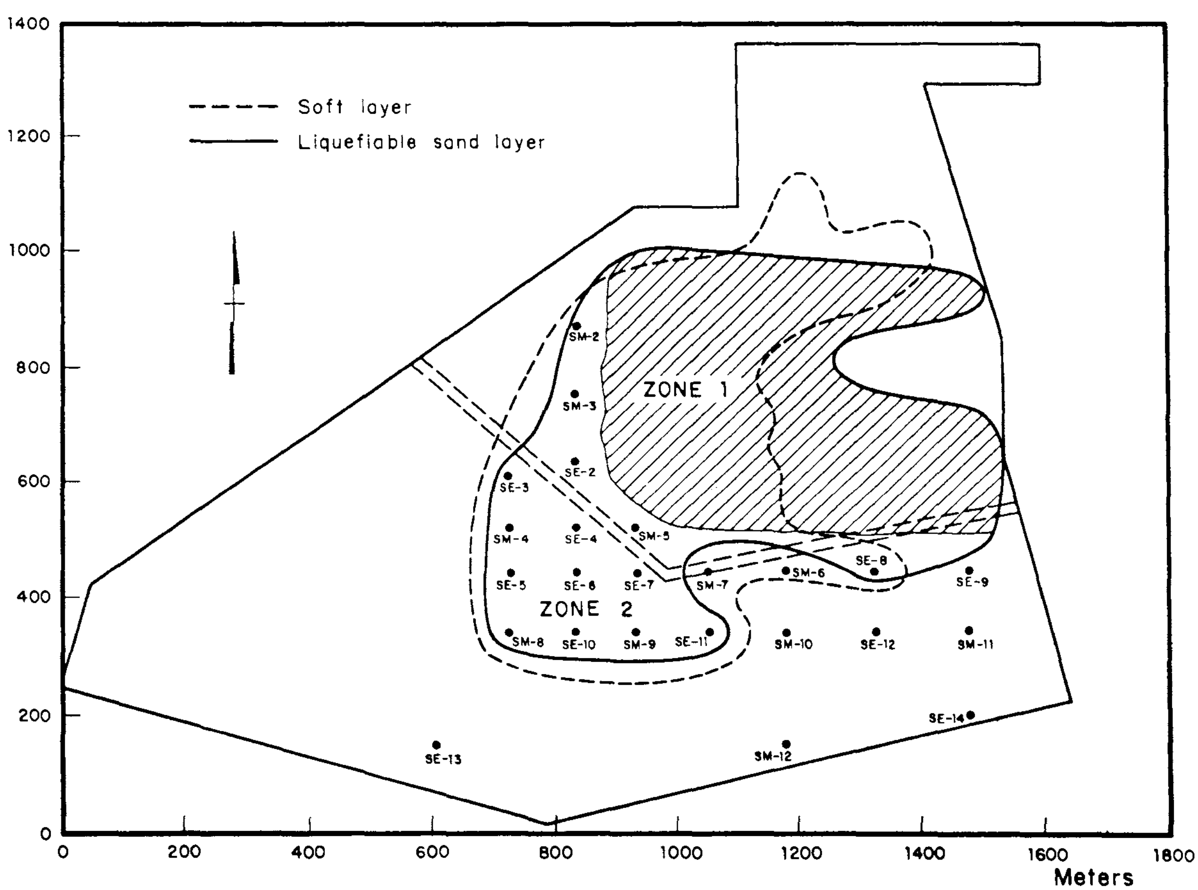


Fig 2. Additional site exploration

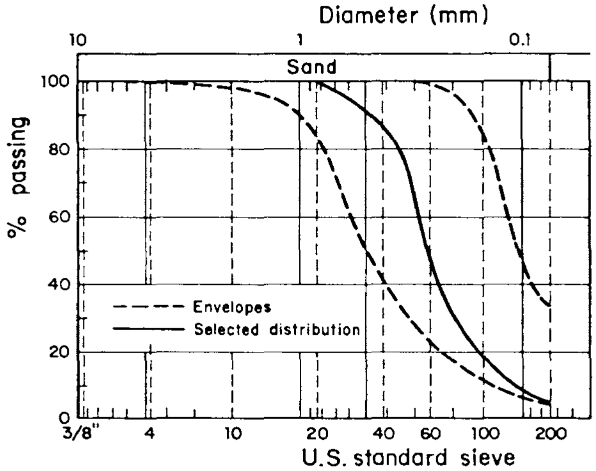


Fig 3 . Envelopes of grain distribution curves and grain distribution selected for cyclic triaxial specimens

TABLE I. Characteristics of Sand Used in Cyclic Triaxial Tests

Grain size	$0.1 < D_{50} < 0.5$ mm $2.43 < C_u < 3.92$ (uniformity coefficient)
Fines content	less than 15%
Grain shape	angular
Minerals	quartz (50%), feldspar (25%), ferromagnesians (10%), rock fragments (7%), mica (3%), seashells (5%)
Bounding	there was no trace
Maximum void ratio, e_{max}	1.02
Minimum void ratio, e_{min}	0.68
Specific gravity, S_s	2.69

A total of six undrained stress-controlled cyclic triaxial tests were performed on saturated specimens of sand compacted to approximately the same density. Standard triaxial test equipment, incorporating a pneumatic square loading system, a force transducer at the base of the sample to measure the cyclic deviator force, a pressure transducer connected at the base and the cap of the sample to measure pore pressure and a LVDT to monitor axial displacements, was used for all tests. Further details of the test equipment are given by Jaime (1978).

The samples were formed using the method of pluviation through water (i.e., saturated sand is poured into a water-filled forming mold and then the mold is vibrated until the desired density is achieved). The samples tested were prepared to a relative density $D_r = 68\%$. This value was selected on the basis of field studies which showed that for the liquefiable sand layer the average SPT blowcounts, normalized to an effective pressure of 1 kg/cm^2, was $\overline{N} = 23$. According to empirical correlations this value corresponds to $D_r = 75\%$; however, the minimum value of $\overline{N}$ reported by Jaime et al (1981) was 15 which corresponds to $D_r = 60\%$.

Once a sample was formed, a small vacuum (approx. 0.1 kg/cm^2) was applied to the top of the specimen, the forming mold removed, and the dimensions of the sample determined with a dial gage to the nearest 0.05 mm. The triaxial cell was then assembled and an external chamber pressure (aprox. 0.1 kg/cm^2) was gradually applied during which the internal vacuum was simultaneosly reduced. Deaired water was then allowed to slowly flow through the sample until it was nearly saturated, and a back pressure (aprox. 2 kg/cm^2) was used to fully saturate the specimen. In all the tests the Skempton's-B coefficient was greater than 0.96.

The sample was then consolidated under an effective confining pressure of 0.6 kg/cm^2, which is equivalent to the average effective vertical stress acting upon the sand layer in the field. Once the sample was fully saturated, the drainage valves were closed, and the specimen was subjected to square cyclic deviator stress applications of constant amplitude. The forces at the sample base and the axial deformations of the sample with increasing numbers of stress cycles were recorded, and the number of cycles required to induce initial liquefaction (pore water pressure equal to initial effective confining pressure, $u = \overline{\sigma}_c$) was determined.

TEST RESULTS

The results of the cyclic tests are presented in Table II, which shows the test relative densities, the values of the cyclic stress ratio (cyclic deviator stress divided by twice the initial effective confining stress, $\sigma_{dc}/2\overline{\sigma}_c$) and the corresponding number of cycles required to cause initial liquefaction, N_ℓ.

TABLE II. Cyclic Triaxial Test Results

Test* N°	D_r %	N_ℓ	$\frac{\sigma_{dc}}{2\overline{\sigma}_c}$
P1	88	212	0.173
P2	68	30	0.172
P3	68	197	0.136
P4	56	35	0.135
P5	62	1	0.298
P6	68	17	0.156

* Samples formed by pluviation through water

Before these results are used in assessing the liquefaction potential of the sand stratum, they have to be adequated to field conditions. Comparing cyclic triaxial test results with the results of cyclic simple shear and of large samples tested in a shaking table, Seed et al (1975) concluded that the values of cyclic stress ratio to achieve failure in triaxial tests are underestimated within the first ten cycles. Thus, they suggested that a correction factor varying from 1.22 for the first cycle to 1 for the tenth cycle should be applied.

Furthermore, it has been recognized that the stress conditions a soil sample is subjected to in a triaxial test are different to those of the field. Several correction factors varying between 0.55 and 0.85 approximately, have been suggested in the literature. In this study a correction factor, C_r, of 0.7 was used.

Finally, in order to take into account the aging, fabric and prestraining (due to previous seismic events) effects on the susceptibility fo the sand layer to liquefy, the values of the cyclic stress ratio were multiplied by a correction factor, which according to Seed (1979) varies between 1 and 2.82, for sands having a relative density of 60%. In this study the factor used was 1.5.

Multiplying the values of cyclic stress ratio reported in Table II by the above mentioned correction factors, the curves shown in fig 4 were obtained.

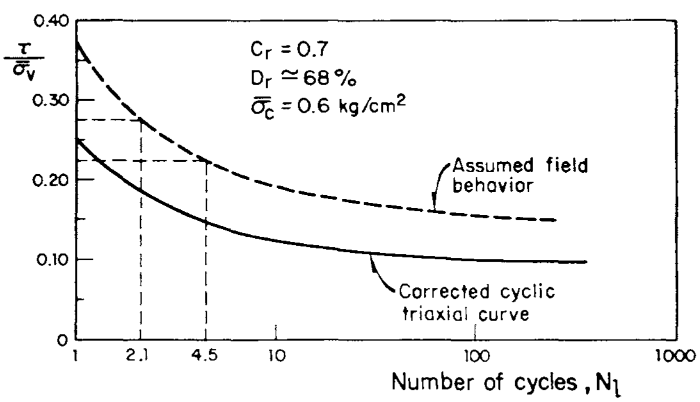


Fig 4 . Cyclic triaxial behavior

LIQUEFACTION ANALYSIS

To have a better understanding of the field behavior of the Enmedio Island soil deposits a liquefaction analysis of the site was performed. The numerical model used was that proposed by Seed, Martin and Lysmer (1975). This model enables consideration of pore pressure generation and dissipation during the seismic event. Hence, a more accurate simulation of the phenomenon is achieved. The numerical computations were carried out with the computer program, GADFLEA, developed by Booker, Rahman and Seed (1976).

With the purpose of investigating the effect of the overburden pressure and of the impervious clay layer on the development of liquefaction, four soil deposits with the stratigraphies shown in figs 5 and 6 were analysed. The average soil characteristics as well as the number of cycles to reach liquefaction and the corresponding cyclic stress ratios are shown in Tables III and IV. The values of N_ℓ reported in these tables were obtained from the cyclic triaxial test results (fig 4) for the sand layer which liquefied, and an arbitrary value of 1 000 was assigned to other layers on the basis of their permeability, fines content and granulometric characteristics. To compute the cyclic stress ratio ($\tau/\bar{\sigma}_v$) induced by the earthquake, the simplified approach proposed by Seed and Idriss (1971) was used.

TABLE III. Characteristics of Soils Used in the Analyses: Zone 1

Depth (m)	Perme-ability* (m/s) x 10^{-3}	Compr. modulus (m^2/ton)	Cyclic Str. Ratio	Number of cycles
0-3.15	0.811	0.001	0.19	1 000
3.15-3.85	0.0018	0.01	0.19	1 000
3.85-7.25	0.0643	0.00076	0.223	4.5
7.25-13.25	0.811	0.001	0.271	1 000

* Lefranc tests

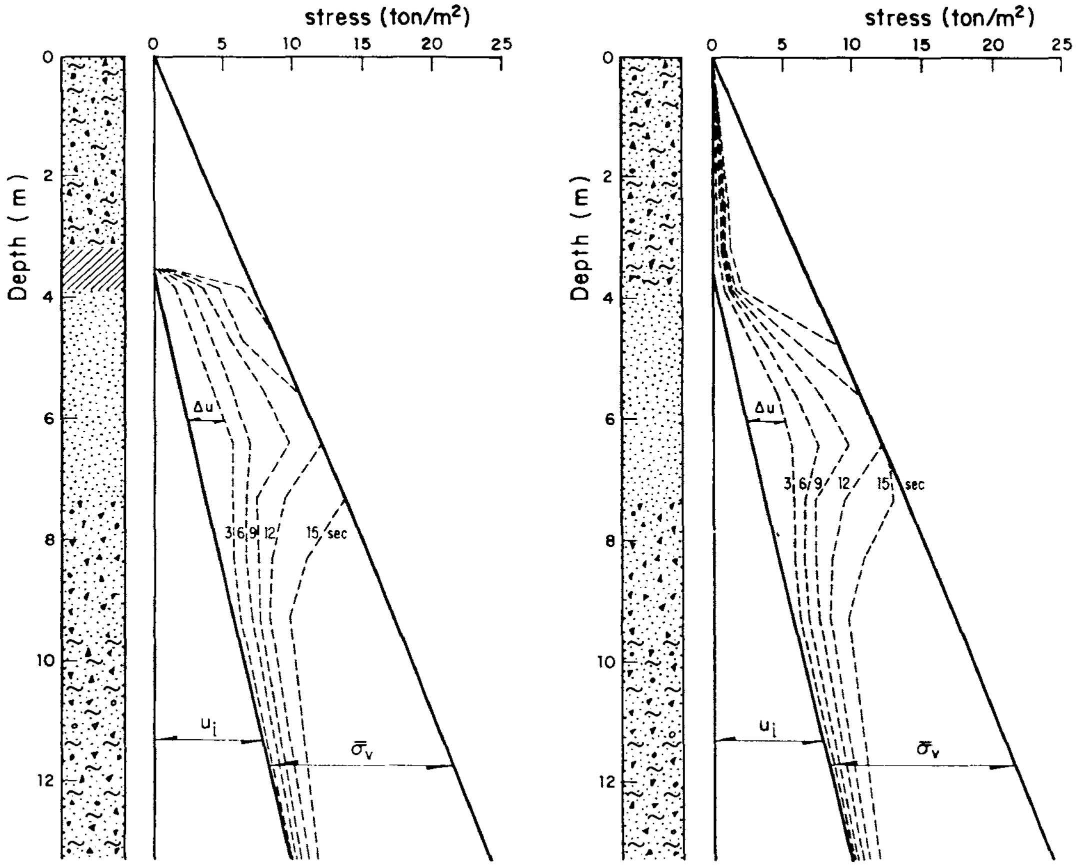
TABLE IV. Characteristics of Soils Used in the Analyses: Zone 2

Depth (m)	Perme-ability* (m/s) x 10^{-3}	Compr. modulus (m^2/ton)	Cyclic Str. Ratio	Number of cycles
0-0.75	0.811	0.001	0.19	1 000
0.75-1.45	0.0019	0.01	0.19	1 000
1.45-4.85	0.0643	0.00076	0.274	2.1
4.85-10.85	0.811	0.001	0.330	1 000

* Lefranc tests

The results of the analyses presented in figs 5 and 6 show that the sand layer liquefied in both zones although the time of occurrence was different. While in zone 1 (fig 5) occurred towards the end of the seismic event (the strong part of the earthquake lasted 15 seconds), in zone 2 (fig 6) liquefaction developed towards mid-time duration of the strong shaking. The field manifestations of liquefaction in zone 2 and their absence in zone 1 can be explained considering that for a sand boil to develop, it is required that the pore pressure reaches a value equal to or greater than the overburden pressure. To achieve this, it is necessary that the earthquake continues delivering energy to the layer of liquefied material for few seconds after initial liquefaction is reached. From the observed field behavior and the analytical results it seems that for the Enmedio Island soil deposits, this span of time is around 5 to 7 seconds.

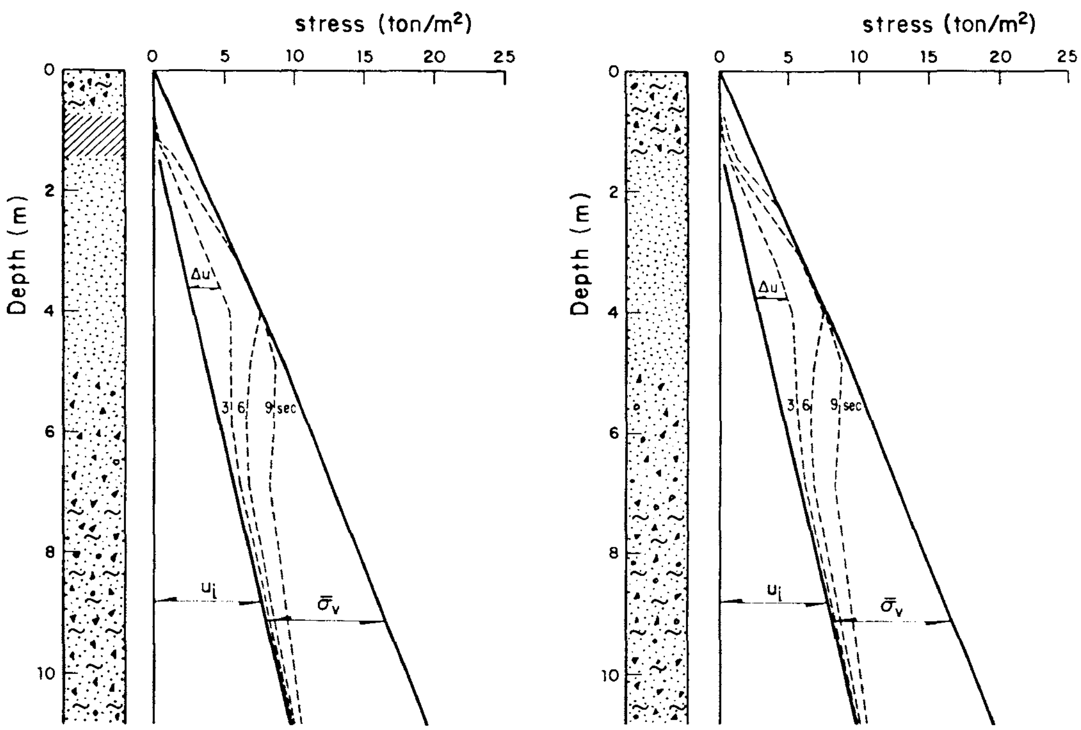
Comparing figs 5a and 5b it is observed that the presence of an impervious clay layer does not affect the development of liquefaction. The same conclusion can be reached comparing figs 6a and 6b. This implies that when liquefaction is developed in a few loading cycles (loose sand layer), the use of drain wells (to decrease the length of the flow path) as ameasure to improve sand behavior upon shaking might not be an adequate practice.



a) Impervious upper boundary

b) Drained upper boundary

Fig 5 . Earthquake – induced pore pressures in zone 1



a) Impervious upper boundary

b) Drained upper boundary

Fig 6 . Earthquake – induced pore pressures in zone 2

On the other hand, an increase in overburden pressure may be an effective practical measure to prevent liquefaction. This is confirmed by the results shown in figs 5 and 6 which clearly indicate that an increase of about 0.4 kg/cm^2 in overburden pressure, retarded the generation of liquefaction of the sand layer in zone 1 by about 6 seconds. This suggests that there exists a threshold value of the cyclic shear stress ratio, below which the increment of pore pressure is limited to certain value less than the effective confining stress regardless the number of cycles. The magnitude of this threshold depends on the soil type, initial relative density and the overburden pressure.

CONCLUSIONS

The results presented in this paper show that liquefaction analyses performed with a method which enables simulation of dissipation and generation of the pore water pressure induced during an earthquake, may help in understanding actual field behavior. The results also indicated that the discontinuous impervious clay layer which was found throughout the Island was not the cause why liquefaction was not observed in zone 1. On the other hand, through the analyses it was demonstrated that the sand layer in zone 1 did liquefied but the phenomenon was retarded with respect to the occurrence in zone 2, due to the effect of the greater overburden pressure in zone 1, and thus there was not enough time for the superficial manifestations to be developed.

ACKNOWLEDGMENTS

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